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Expert Approaches to Analysis

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Study of how scientists and military analysts make sense of complex situations with the goal of developing an elaborated theory of epistemic forms and games, which can form the basis for building a tool to support expert analyses.

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Introduction

There are recurring patterns or forms that are found among expert analyses. Some of the different forms that these analyses take are cost-benefit analysis, stage models, hierarchies, trends, and multi-factor models. Learning to analyze complex situations implies mastering how to carry out investigations of phenomena guided by one or more of these target structures. We refer to these target structures that guide analysis as epistemic forms, and the set of rules and strategies that guide analysis as epistemic games.

Everyone engages in the most basic epistemic games: list making, compare and contrast, constructing causal chains, determining the steps in a process, analyzing trends, etc. Research and practice have elaborated these basic strategies by adding specialized constraints. By exploiting these constraints systematically, experts can more productively explore any domain of inquiry.

In prior work we have constructed a preliminary theory of the epistemic forms and games experts use to conduct inquiries (Collins & Ferguson, 1993; Morrison & Collins, 1995). In our current work for ARI we studied how scientists and military analysts make sense of complex situations. Based on our analysis of these data, we have developed an elaborated theory of epistemic forms and games, which can form the basis for building a tool to support expert analyses.

We would argue that this research will be useful both in developing expert advisory systems and in training military commanders. For example, the kind of system we propose to develop could be used to provide both tools and advice to experts for analyzing complex situations. With respect to training, we would argue that it would be useful for future military commanders to learn some of the most important epistemic forms and games to guide their analyses. They have value in any endeavor to understand the world.

Prior Work

This section briefly summarizes the preliminary theory developed in Collins and Ferguson (1993). We divide epistemic games into three types: structural-analysis games, functional-analysis games, and process-analysis games.

Structural-Analysis Games

One of the simplest epistemic games is list-making. People often make lists as part of carrying out their day-to-day activities, but they also make lists in an attempt to understand the world. Every list is implicitly the answer to a question. Some epistemic questions might be "What are the basic substances things are made of?" "What are possible courses of action to win a battle?," and "What were the causes of the French Revolution?" If the answer to these questions must be discovered, rather than recalled or looked up, then the list-making process is an inquiry process and the resulting list constitutes new knowledge.

List-making can be elaborated by adding constraints on the contents of the list. These constraints are the rules of the game and serve two purposes. They cause the resulting list to be more focused and they facilitate the finding of ideas. The constraints established by the list-making game that we have identified are: **similarity**, **coverage**, **distinctness**, **multiplicity**, and **brevity**. Similarity is the requirement that the items in the list be of the same general form: the same scale, the same kind of thing, of the same importance, and so on. Coverage means that all possible answers to the question are covered by the items on the list. Distinctness requires that no two items overlap or are difficult to distinguish. Multiplicity means that a list must have more then one element. Brevity refers to the fact that short lists are generally better than long ones, because they constitute more succinct answers to the inquiry.

Each of these constraints leads to useful list-constructing strategies in the form of auxiliary questions that may help to guide the inquiry. Similarity provokes the question: "Is one of these things not like the others?" Coverage asks "Has anything been left out?" or "Is every example I can think of covered by one of the items in the list so far?" Distinctness leads to asking "Do any of these items overlap or mean the same thing?" Multiplicity is a definitional constraint and really only leads to the question "Am I really seeking a list?" when only one item can be thought of. Finally, brevity (when a list begins to grow too large) prompts questions like: "Should I be using more abstract categories?" or "Can the elements of this list be partitioned in some way?" The questions generated by violations of the brevity constraint often lead to major shifts in the nature of what is being listed. The magnitude of the developing list may push one into deciding to use much larger classes, or to change games altogether by trying to form a hierarchy or a table.

The desired result of any epistemic game is the completion of an epistemic form that satisfies the inquiry. Because of this correspondence, the names of the games and forms are often similar — the list-making game produces lists, the system-dynamics game produces system-dynamics models, and compare and contrast produces a comparison table. But the same form may be produced by more than one game; for example the primitive-elements game also produces lists.

The list game is the simplest structural-analysis game, but there are others. The most similar to the list game are spatial and temporal decompositions (i.e. stage models). More complicated structural-analysis games include compare-and-contrast, cost-benefit analysis, primitive-elements analysis, tables or cross-product analysis, and tree structures or hierarchical analysis. Structural-analysis games answer the question "What is the nature of X?" by breaking X down into subsets or constituents and describing the relationships among the constituents. We briefly describe each of these games.

Spatial decomposition is the kind of analysis that takes place in anatomy or circuit diagrams. The goal is to break an entity down into a set of non-overlapping parts, and to specify the topographical relations between the parts. The set of constraints is the same as the list-making game, though each has a spatial aspect. Specifying the topographic connections is an additional constraint, and where applicable, specifying the nature of these connections is another constraint.

Temporal decompositions or **stage models** are common in historical analysis, psychological analysis, and analysis of any process that is characterized by a series of states. The simplest stage model is a list constructed with the constraint that the stages follow each other sequentially without overlap.

Figure 1 shows a more complicated version of a stage model, and illustrates the way we represent epistemic forms. Each stage might be characterized by multiple characteristics, and furthermore these characteristics may be arranged on a set of dimensions (e.g., the boy was angry and tired before his nap, but happy and energetic afterwards). In a more complicated stage model, the interrelationship between the variables might be specified (e.g., energy state determines mood), and the reason for the change from one stage to the next specified (e.g. a nap leads to an increase in energy state). These last four constraints (i.e., multiple characteristics, specified dimensions, specified interrelationships, and reasons for transition) are all optional constraints that a person might or might not use in constructing a stage model.

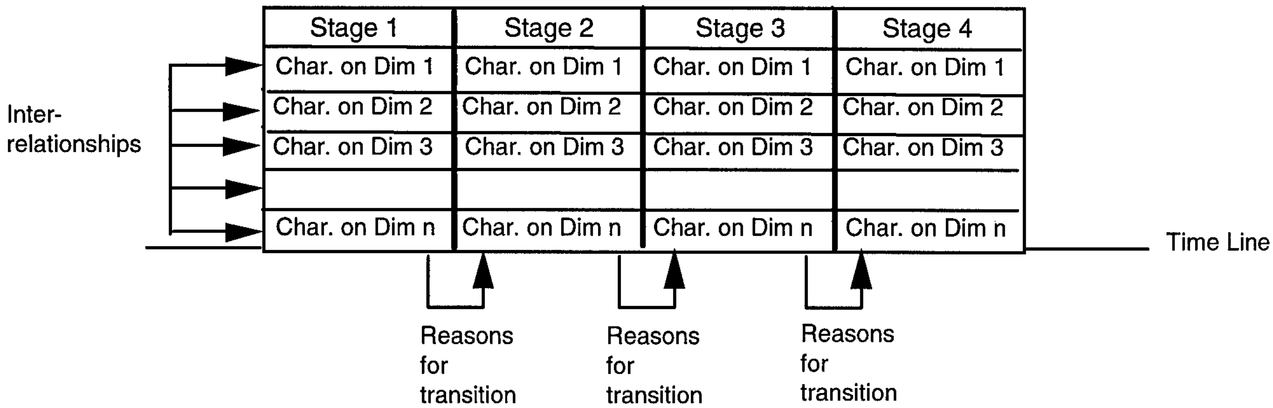

Figure 1. Stage Models

Compare and contrast is a decomposition game involving comparison of two entities. It is commonly used in beginning analysis in many different fields, but is perhaps most prominently seen in history and the social sciences. The most common version of this game employs dimensional analysis, where the common and distinctive features are identified with particular dimensions.

Cost-benefit analysis is a special case of compare-and-contrast, that is used in social and economic policy analysis. The things compared in cost-benefit analysis are alternative courses of action, and in playing this game one should first identify all possible courses of action (i.e. the coverage constraint in the list game). Then one tries to identify all the costs and benefits (or pros and cons) of each alternative. This might also involve a set of dimensions on which the alternatives are compared, such as time, effort, and money. Identifying all the costs and benefits (i.e. to obtain coverage) for each alternative is aided by knowing about likely kinds of costs and benefits, such as time, money, and effort; it is also aided by knowing to look for possible side effects, for social as well as individual effects, and for possible countereffects and synergies.

The **primitive-elements game** is a version of the list game that has driven much of the history of the physical sciences and now is playing a large role in artificial intelligence analyses of the social sciences (e.g. Schank & Abelson, 1977; Waltz, 1975). Chemistry identified 92 natural elements, and when atoms were discovered, the quest was to determine the basic elements from which atoms are made. The latest attempt is to determine different types of the primitive elements (i.e. quarks) making up protons, neutrons, and other subatomic particles. Coverage of all the phenomena by the set of primitive elements is particularly critical in this game. Another constraint is to specify how the elements combine to produce each phenomenon.

The **cross-product** or **table game** is a multi-dimensional version of the list game. The best known example of the cross-product game was the construction by Mendeleev of the periodic table of chemical elements. This led to identifying missing elements and ultimately to an understanding of the atomic structure of molecules. The dimensions can be continuous or discrete, and cells can multiply filled or not. These latter constraints have a large effect as to how the cross-product game is played. But as in the primitive-elements game, coverage of all the elements is a critical constraint in playing the cross-product game.

The **tree-structure** or **hierarchy game** is familiar to everyone from its use in biology. Often the tree-structure game is employed as a transfer from the list game when a list gets too long. The added constraints in a tree structure are that the elements be broken into subsets of similar types (the similarity constraint) and the relations among the subsets be specified. These kinds of hierarchies pervade the biological and social sciences, since evolutionary processes naturally produce tree structures.

These are the most common structural-analysis games. Most employ the constraints described for the list game, but each adds new constraints. They are the basis for understanding the structure of systems, and this is a major form of inquiry that is carried out in analyzing situations.

Functional-Analysis Games

A second major form of analysis is functional analysis. The goal in this kind of analysis is to determine the causal or functional structures that relate elements in a system. The most common functional-analysis games include critical-event analysis, cause-and-effect analysis, problem-centered analysis, multi-factor analysis, and form-and-function analysis.

Critical-event analysis occurs in historical analysis and troubleshooting of various kinds (often called critical-incident analysis). This kind of analysis centers on a particular event (e.g. an airplane crash or invention of the printing press). It attempts to identify the events or causes that led to the critical event or the set of consequences that flow from the critical event.

Cause-and-effect analysis is a variation on critical-event analysis that assumes a sequence of events, each one leading to the next. It is frequently used in constructing artificial intelligence models of events. The analysis distinguishes triggering events or causes from preconditions, which are necessary conditions for the effects to occur. Each effect in turn can be the triggering event for a new set of effects.

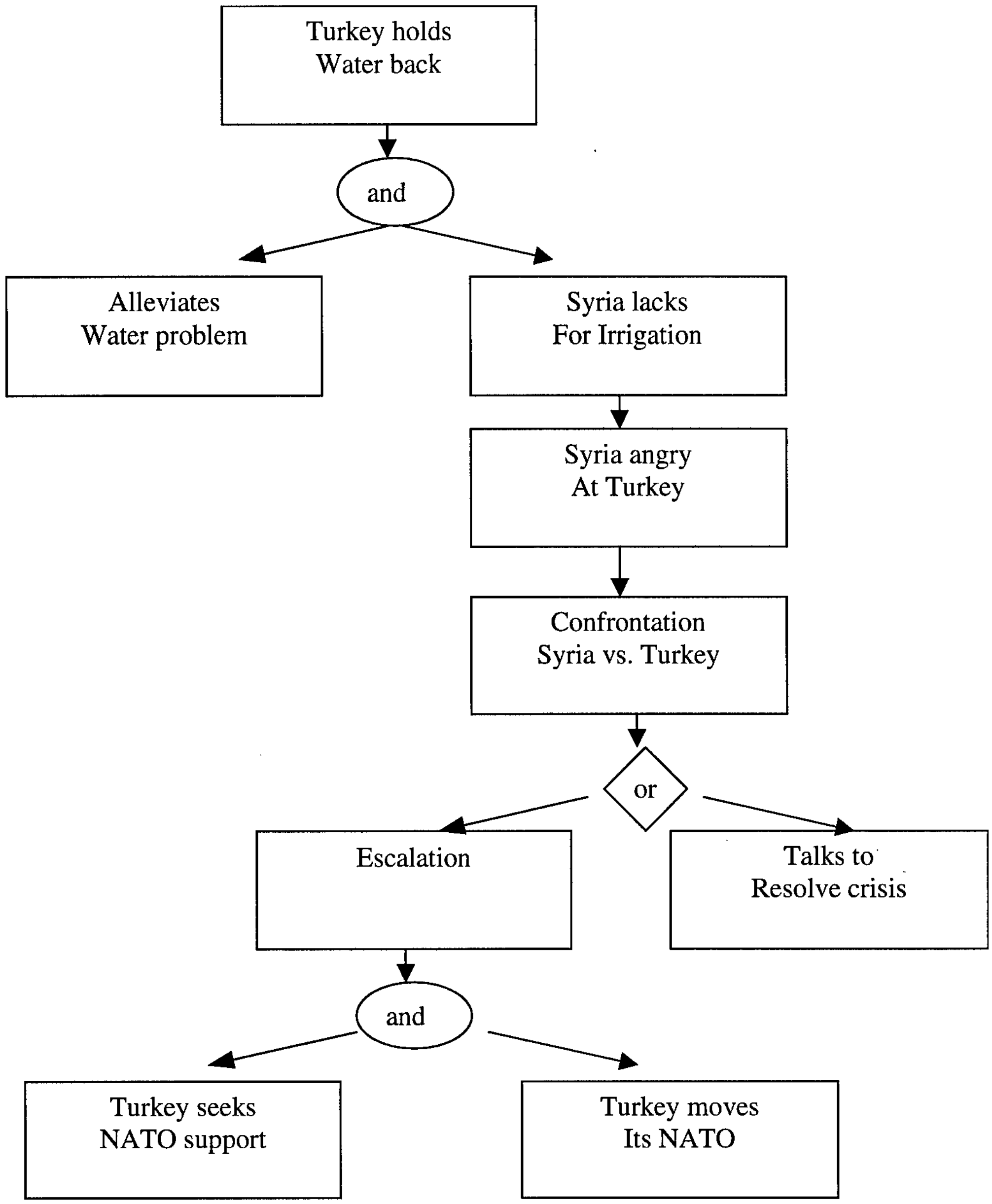

Figure 2: Figure 1 Military analyst's beginning analysis of water rights problem

Problem-centered analysis is found throughout history and any subject area where human goals and actions are paramount. The simplest form of this analysis breaks an event stream into problems and actions taken to solve the problems. These actions lead to main effects and side effects. Problem-centered analysis is embodied in the formal analysis of human-computer interaction by Card, Moran, and Newell (1983), and the analysis of electronic troubleshooting behavior by Hall, Gott, and Pokorny (1992). In a variation on the Card, Moran, and Newell analysis, the latter break the stream of events into problems, actions, results, and interpretations (called PARI analysis). Each interpretation identifies a new problem to be solved unless the goal state has been reached.

Multi-factor analysis or **AND/OR graphs** are another common way to analyze causality in systems. They are particularly pervasive in geography and medicine, but are common in many other disciplines where it is difficult to identify a chain of events that are causally interlinked. In multi-factor theories, variables (called factors or independent variables) are linked together in a tree structure. The branches of the tree are ANDed together if a set of factors are all necessary to produce the desired value on the dependent variable. They are ORed together if any of the factors are sufficient to produce the desired value on the dependent variable.

Form-and-function analysis involves different structures depending on the field of inquiry. The simplest analysis is to distinguish between the forms of objects and their functions or uses. Weld (1983) used a more sophisticated form-and-function analysis to characterize explanations of the workings of physical devices, such as a car engine in terms of roles, functions, structures, and mechanisms. Another artificial intelligence researcher (Edelson, 1993) represented the knowledge extracted from interviewing a biology professor about animal behavior in terms of an elaborated form-and-function analysis specialized for biology.

These various kinds of functional or causal analysis forms guide inquiry by providing target structures that can be used for analyzing phenomena or events in the world. Such functional analysis pervades human being's attempts to make sense of the world around them (Perkins, 1986).

Process-Analysis Games

In addition to analyses in terms of structure and function, a third kind of analysis of phenomena is in terms of their dynamic behavior. We have labeled the various epistemic forms and games designed to make sense of dynamic phenomena as process analyses. The major forms and games we will discuss are system-dynamics models, aggregate-behavior models, constraint-system analyses, situation-action models, and trend analysis.

System-dynamics models are increasingly common, especially in the social and physical sciences. There are a variety of computer programs, such as STELLA, that provide tools for constructing system-dynamics models. Such programs in fact provide a generative epistemic form for playing the epistemic game of system-dynamics modeling. The basic elements in system-dynamics models are variables that can increase or decrease. These are linked together by positive or negative links, usually with feedback loops permeating the system of variables.

Aggregate-behavior models are constructed frequently to explain behavior in the physical sciences, particularly the behavior of small particles like molecules and electrons. The models assume random, parallel motion of a large array of particles. When the particles encounter each other, there are a number of possible interactions, such as sticking together, rebounding, or breaking apart, that occur under different conditions. When they encounter a barrier, there also are a set of possible interactions, such as penetrating it, rebounding from it, or sticking to it, under different conditions. These kinds of models are characteristic of diffusion models, chemical mixtures, statistical mechanics, origin-of-life models, and DNA replication.

Constraint systems have permeated our understanding of physical systems since Galileo. They are characterized by a set of equations describing the steady state behavior of a system. Constraint systems are regarded as one of the most precise forms in which to state a theory. The epistemic game most associated with this epistemic form is the controlling-variables game developed by Galileo, where one tries to manipulate one variable at a time while holding other variables constant, in order to determine the effect of each independent variable on the dependent variable.

Situation-action (production-rule) models are commonly used to describe behavior in the social sciences (e.g. Newell & Simon, 1972). They are characterized by a set of rules of the form "If in situation x, do y." The situation can change either because the world changes or because the agent takes an action. Markov models and grammars can be considered as special cases of situation-action models, where each action takes one into a new state and where different actions are possible in each state.

Trend analysis is most commonly found in economics and history, but can be used to analyze any set of variables that change over time. A classic example of this kind of analysis is Milankovitch's analysis of how the earth's ice ages depend on cyclic variations of the earth's tilt, the shape of the earth's orbit, and the precession of the orbit. Milankovitch showed how precise predictions can be made from such a model.

Process analyses attempt to characterize the behavior of dynamic systems. The process-analysis games we have identified are very diverse, and appear to share fewer characteristics than the structural-analysis and functional-analysis games. The groupings of games is put forward as our best hypothesis as to which games share the most constraints.

We have briefly described some of the most common epistemic games and the epistemic forms that are associated with them. This is not a complete list, but it does serve to illustrate the potential of the concept of epistemic forms and games. Mastering any of these games gives one a powerful tool for making sense of different phenomena in the world.

Protocol Experiments on Expert Analysis

Method

In our current ARI contract we have collected and analyzed protocols from expert military analysts and scientists. In order to collect protocols from military analysts, we visited the War College in Carlisle Pennsylvania to obtain military scenarios they use as training exercises. We obtained a number of scenarios they had developed and have collected protocol data, using three military experts as subjects, on two of these scenarios. One of the scenarios concerns a confrontation over water rights between Turkey, Syria and Iraq and the other concerns piracy in the Straits of Malacca near Singapore. We identified eight stopping points in the first scenario and five in the second, where the subjects were asked "to analyze as thoroughly as possible what the situation is and to make a detailed prediction as to what you think will happen next." For the first scenario, a former Colonel in the Army worked alone, and a former Lieutenant General in the Army and a former Colonel in the Marines worked jointly. For the second scenario all three worked together. All the sessions lasted less than two hours.

The science protocols were collected from a physicist, biologist, psychologist, and historian, who worked individually on four questions for two to three hours each. The four questions covered a range of topics in the biological, physical, and social sciences, including history, and relevant materials were provided. The questions were meant to require different kinds of solutions, such as predictions, explanations, policy decisions, and analysis of patterns in data. The four questions were:

- **What is the cause of declining wages in America and what should we do to reverse the decline?** The materials consisted of five books with different views and explanations, ranging from economic to political to demographic.
- **How will the climate of the Earth change over the next 10 to 10,000 years? Please project the changes over the entire period.** The materials consisted of about 20 articles about climate changes discussing various change agents, such as carbon dioxide, dust particles, orbital variation, sunspot variation, etc.
- **How do teenagers in different countries differ?** Subjects were given a book titled The Teenage World with a large data set from ten countries of teenagers' answers to about 100 psychosocial true/false questions, separated by sex and age. The text described patterns the researchers identified in the data.
- **What do you predict for the world's resources and environment over the next 50 years? Make explicit predictions at least about food, energy, materials, pollution, and wildlife.** The materials consisted of several books and articles giving trend data, explanations for the trends, and future projections.

We counterbalanced the order of the problems across subjects and asked them to work according to the following instructions:

1. Your task is to analyze the problem given and come up with your own solution or theory to address the problem.
2. When you are finished analyzing the problem, we want you to write up your solution in some form, such as text, a figure, a table, or preferably a combination of these.
3. You will have 2-3 hours to work or longer if you need the time, but you should try to finish in 2 hours.
4. Spend as little time as possible reading. Try to work through the problem using the materials as a reference.
5. Your job is to construct your own analysis of the problem. Do not give us the solutions or theories of the authors you are reading.
6. Bring in whatever knowledge you have from other sources. Try to identify what that knowledge is and its source.
7. Try to make integrative notes and representations of your thinking as you go along. The more detailed your notes, the better.
8. Explain your thinking as you go as thoroughly as possible into the tape recorder. You can pause the tape recorder while you read, so we do not get a lot of blank tape.
9. Try to write down and say what your current solution is as you go along, explaining why you think what you do and why you make any changes in your view.
10. If you change your mind about something, make a special effort to make note of the change and what caused it. It is easy to not notice you are changing your mind, so please make a special effort to notice any change.
11. When you start generating a particular representation, try to say where it came from.
12. Do not feel you need to read or even look at all the materials. Select those that interest you most and focus your investigation however you think is most productive.

Analysis of the Protocols

In our analysis we have identified six different kinds of elements that the experts are using to analyze these complex problems: **epistemic forms** (target structures for the analysis), **epistemic games** (analysis strategies), **domain frameworks** (organizing structures for guiding an analysis), **key constructs** (key variables that enter into different types of models), **heuristics** (rules of thumb, such as to look for positive feedback loops or lag effects), and **prompts** (issues raised for consideration by the experts). Below we discuss each of these and the role they have played in the protocols.

Epistemic Forms. Epistemic forms are the target structures that guide the experts in their analysis. There is a progression of forms we have noted in the protocols, where subjects nest one kind of analysis inside another kind of analysis. For example, they often used a structural-analysis form, such as a list or stage model; in order to make a decomposition of the problem. Then within each component, they used another analysis form, such as a trend analysis or a cause-and-effect analysis, to elaborate their analysis. As another example of how they nest their analyses, they would sometimes start working out causal chains, which they then would develop into multi-factor models. In one case the biologist extended his multi-factor model into a system-dynamics model. Thus the analyses they constructed involved complex nesting of different epistemic forms.

There are ten epistemic forms that we identified in the protocols:

- **Cause-and-effect analysis.** Both the military analysts and the scientists spent a large amount of time constructing causal chains. The causal chains constructed had the following form: $S(a) \Rightarrow S(b) \Rightarrow S(c)$, where S is a state. In the military protocols, the links were often assigned qualitative likelihoods. The chains were of different lengths, but most contained two or three links. An example of this kind of analysis for the water-rights scenario is shown below:
- **Multi-factor models**. In several of the problems the experts attempted to create a multi-factor causal model in the form of an AND/OR graph. As an example of this kind of analysis created to account for why real wages have declined in America during recent year, one scientist constructed a multi-factor model, where the key constructs were labor supply, labor demand, technology, global competition for jobs, the baby boom entering the workforce, women entering the workforce, increasing costs of benefits, and trade policies. These factors were linked together to account for the declining wages, based on a supply-and-demand framework.
- **Cost-benefit analysis.** In the military protocols, the subjects often considered different possible courses of action and the costs and benefits associated with each. In one case they considered three possible courses of action with respect to dealing with pirates in the Straits of Malacca: (1) Putting pressure on Indonesia to deal with the pirates, (2) taking unilateral action against the pirates, and (3) organizing a multilateral force against the pirates. We can illustrate the kinds of costs and benefits they considered in terms of multilateral action. The benefits they considered for multilateral action were spreading costs over more parties, adding legitimacy, and building relationships with countries in the region. The costs involved the difficulty in taking decisive action and the extensive negotiation and time it takes to put together multilateral action. The analysts updated their cost-benefit analysis as the situation unfolded in the scenario. There are classes of costs and benefits (e.g., financial, international relations) that we have begun to enumerate based on our analyses. While the problems given the scientists did not lead them to use cost-benefit analysis, an earlier protocol we collected from a scientist, as to how New York City should dispose of its garbage, involved an extensive cost-benefit analysis.

- **Comparative analysis.** A variation on cost-benefit analysis occurred in analyzing the piracy problem when two of the analysts engaged in an argument as to whether Indonesia or China might be helping the pirates, since they were operating down near Singapore. This led to a comparison of arguments for and against China and Indonesia, as below:

	Arguments For	**Arguments Against**
China	Reports of talks w/pirates Diversion from Spratleys, Where China seeks oil	Not clear what they would gain Cannot patrol the Straits
Indonesia	Their navy ships involved Pirates in waters near Java	Assoc with rebellion in Sumatra Pirate bases in Nicobar Islands

- **Trends.** Both on the climate problem and the resources problem the scientists produced trend analyses, based on their understanding of the types of functions (e.g., exponential curves, normal growth functions) that characterize different processes. For example, on the climate problem the psychologist started identifying key variables and their effects on climate trends. When he came to plotting his predictions, he ended up with three phases. The first was an exponential increasing function caused by the increase of greenhouse gases, partially offset by orbital variation and pollutants. The second phase was a decreasing function down to a level below current temperatures, caused by orbital variation as people reduce greenhouse gases. The third phase showed an increasing asymptotic function up to some optimal level near current temperatures, as humans learn to control temperature through greenhouse emissions or other mechanisms. His predictions combined two of the epistemic forms: stage models and trend analysis.
- **Stage or phase models.** The military analysts created phase models to characterize how confrontation processes unfold over time. This arose in the analysis of the water-rights problem where the analyst decided that Syrian military moves were for show, because the confrontation was still in the negotiation phase. One such stage model functioned as a domain framework that organized the entire analysis, as described below. We saw an example of how scientists constructed stage models in the example above.
- **Lists.** In the protocols, the subjects frequently used a list analysis to decompose the problem into components. For example, one subject in predicting the fate of different species, broke them into three types: animals that humans would save (e.g., gorillas), animals that thrive in conjunction with humans, and animals that would likely become extinct.
- **Spatial decomposition.** In a variant on list making, the military analysts on the piracy problem went through each of the countries in the area to determine their goals and how they might be encouraged to act to stop the piracy.

- **Finite state models.** The physicist in working on the wages problem created a simple two-state model, which is a special case of a finite-state model. The two stable states he depicted were: 1) high wages, women not working, family income = x, and 2) low wages, women working, family income = x′, where x and x′ are not very different. He characterized recent decades as moving from state 1 to state 2, brought on by World War II and the women's movement.
- **System-dynamics model.** The biologist in working on the resources problem created a system-dynamics model, where he tried to incorporate all five of the variables (food supply, energy, materials, wildlife and pollution) specified in the problem with six other variables (e.g., climate, technology, policies) in a complex interaction pattern, with multiple feedback loops.

Epistemic Games. In the Collins and Ferguson (1993) paper there was implied coupling between epistemic forms and games, such that there was one game for every form. The protocols show that while there are epistemic games associated with each form, some analysis strategies are not associated with specific epistemic forms. The multi-purpose analysis strategies that we have identified in the protocols are:

- **Hypothesis formation and testing**. Subjects often formulated hypotheses about what the situation might be or what might happen. For example, one military expert hypothesized that Syria and Iraq might attack Turkey in the water-rights situation. Then he went through the scenario as it unfolded looking for evidence that Syria and Iraq were planning an attack.
- **Looking for and explaining anomalies.** The historian used a variation on the hypothesis testing strategy that is worth noting. In the teenage problem, she would test different hypotheses looking for cases (either properties or types) that did not fit the overall pattern. Then she would try to construct a causal chain that would account for the anomaly. The military experts in the piracy scenario used a similar strategy in trying to explain an anomaly about why there was an attack in the Straits of Malacca near Singapore, when the pirates were supposedly based in the Nicobar Islands. They suspected that the pirates must therefore be receiving help from some country in the region.
- **Identifying factors or key constructs.** Much of the thinking and reading that subjects did was directed toward identifying factors that they think may have an influence on the dependent variable in question. For example, in the piracy scenario different experts raised the issues of multilateral action, the legality of the US to send in forces, whether the Straits were international waters, what countries would be affected by the piracy, etc. Also on the wages problem the scientists tried to identify factors, such as women entering the work force, that might tend to drive down wages. These key constructs entered into all the different types of epistemic forms they created.

- **Constructing causal chains.** Both military experts and scientists often construct casual chains by which one event or variable affects another event or variable. The military experts sometimes assigned qualitative likelihoods to the causal links. In addition to creating cause-and-effect models, the causal chains also support construction of multi-factor models and a strategy of countering the weakest link (described below).
- **Countering the weak links.** Military analysts often constructed ways to prevent bad consequences they foresaw. Similarly the scientists were asked to propose solutions to the problem of declining wages. There were two counterplanning strategies used for addressing such issues. The main strategy was based on identifying weak links in a causal chain and then figuring out a way to counter those links. For example, in the water-rights problem the goal was to avoid a military confrontation, so one suggestion was to provide mediation between the parties to the dispute.
- **Countering from strength.** The other counterplanning strategy used was to start with something you know how to do well and applying that to the problem at hand. So for example, two of the scientists attacked the problem of declining wages by specifying different ways that education might address the problem.

Domain Frameworks. It was striking that both military experts and scientists used general frameworks that organized both large and small portions of their inquiry. We have labeled these domain frameworks, because unlike epistemic forms and games they are full of domain-specific content. In fact they are instantiations of particular epistemic forms. For example, one military analyst used an instantiated stage model (described below) to guide his analysis in the water-rights scenario. There was abundant use of analogies in the protocols, and we think they are functioning as domain frameworks. We will give four examples of domain frameworks organizing an inquiry, but there are many more contained in the protocols.

- **Confrontation phase model.** A military expert interpreted developments in the Turkey-Syria-Iraq water rights problem in terms of a three-phase model of confrontation. In the first phase, the negotiation phase, there is an effort by the conflicting parties to resolve their differences peacefully with the help of mediation. Any military maneuvers that occur before this phase is completed are mainly to show serious intent. The phase ends when negotiations fail, which leads to military preparation. The preparation phase consists of moving troops and supplies into position, and ends in military attack. At any time during the preparation or attack phases, the process can return to the negotiation phase, but this usually does not occur until a stalemate is reached.

- **Law of supply and demand.** The scientists attacked the wages problem using the law of supply and demand to organize their search for factors that might cause a decline in wages. To do this they looked for things that might increase the supply of labor or decrease the demand for labor or for goods produced by the labor. Supply and demand is a complex concept with many facets and it clearly played a large role in the inquiry. But it is an instantiated theory rather than an epistemic form.
- **Frontier metaphor.** The historian in working on the resources problem invoked the parallel to the American frontier, where people would move on to new territories when all the land was taken. She came to see resources as like the frontier and so organized her inquiry around the way that people would move on to other resources when the old ones were used up.
- **Principle of attacking when your opponent is diverted.** One military expert applied a general rule of aggressive behavior by countries in trying to predict what Iran might do in the water-supply problem. The framework he used had the general form that if your opponent (e.g., Iraq) is occupied with a problem (e.g., Turkey), then this is an opportune time to move against your opponent. These kinds of domain-inference frameworks were used quite frequently to make predictions in the military protocols.
- **Lester Brown vs. Julian Simon model of resources.** In working on the resource problem, the psychologist started his analysis based on one of the readings with a domain framework we call the Lester Brown model of resource depletion. In this view, land for growing crops is being lost to soil erosion, salination, and other uses, natural resources are finite and are being used up, and we are reaching the point of diminishing ability to increase resource production to accommodate increasing population. But after pursuing this framework for a short while, he switched to another framework we call the Julian Simon model of infinite resources, based on one of the readings among the materials provided. He used the Simon model thereafter in making predictions about food, energy, and mineral resources. According to the Simon model the cost of resources over the long run always decreases, because of substitution, improved production techniques, and opening up of new sources. The decreasing cost reflects increasing supply relative to demand.

Key Constructs. All the subjects identified key constructs that they worked from in building causal chains, multi-factor models, and in one case a system-dynamics model. These are concepts like the Munich pact in history or money supply in economics. They function as the building blocks in any type of theory the subjects develop. We will give four examples of key constructs different subjects used.

- **Islamic War.** One military analyst invoked a notion of an Islamic War with the West as a dangerous possibility that actions should be taken to avoid. This notion of an Islamic War invokes the notion that a number of Islamic countries get together, as they have in the past to attack Israel, to fight attempts by Western powers to control their behavior or impose their culture. The military experts invoked a number of such scenarios (e.g., a cutoff of oil by Islamic countries, a Greek-Turkish confrontation) in order to infer what different parties are likely to do in a given situation.
- **Labor supply, etc.** The scientists referred to the key variables of labor supply, labor demand, supply of goods, and demand for goods, in working through the declining wages problem. These are variables that come out of the supply-and-demand framework that subjects used to organize their analysis of the problem. These are what are referred to in the psychological literature as "intermediate constructs."
- **Negotiations, military preparation, attack.** The key constructs in the military protocols included the different phases that military confrontations go through. These constructs emerged out of the domain framework that the military experts used, just as variables, such as labor supply and demand for goods, arose out of the supply-and-demand framework that the scientists used.
- **Greenhouse effect, etc.** All of the scientists, as they worked on the climate problem, identified a number of controlling variables. The greenhouse effect and orbital variation were the largest of these variables. One subject saw his first task as identifying all of the key variables that affect climate, and then determining which had the greatest effect.

Heuristics. Often subjects talked about processes and effects that were part of their toolkit for understanding the phenomena that they were dealing with, but that were less elaborated than the domain frameworks and more content specific than the epistemic forms. We call these heuristics.

- **Time course.** The military experts referred to the time course over which different phases of events occur. For example, negotiations or deploying warships to protect merchant ships from pirates, have a particular time course to have effect. They used these time estimates to interpret events that were happening.
- **Lag effects.** Several of the subjects talked about lag effects or time delays in problems where predictions and remedies were called for. So for example in the climate problem the scientists talk about the time delays between when humans do something (e.g., releasing carbon dioxide) and its full effects are felt (e.g., earth warming). They arose in the military protocols in terms of how long it would take to put a coalition together or to move troops into position. Lag effects then are used to explain certain kinds of system dynamics.

- **Feedback loops.** There are two kinds of feedback loops that the subjects used in making sense of the problems, positive and negative feedback loops. In the military scenarios, feedback loops occur when countries take actions that lead to escalating actions by adversaries. The scientists also described feedback loops, such as when the physicist noted that snow leads to increased reflection of heat into the atmosphere, causing further cooling.
- **Likelihood of effects.** In the military protocols the subjects often referred to the likelihood that certain events would lead to other events. This sometimes occurred in the science protocols, when human actions were invoked to explain what might happen in the climate, wages , and resources problems.
- **Size of effects.** Another important notion that came up in several of the science protocols is the relative size of different effects. This idea was used at least by the psychologist to discount certain factors that he did not think would affect a dependent variable as much as other factors. In fact he spent a fair amount of time on the climate problem trying to determine the relative size of effects of carbon dioxide and orbital variation.
- **Positive vs. negative consequences.** The military analysts made an important distinction between positive consequences and negative consequences, always with respect to a particular party, such as Turkey or NATO. The assumption was that parties would take actions intended to produce positive consequences and would avoid actions likely to lead to negative consequences.
- **Side effects.** Finally several of the subjects described certain effects as side effects, implying that they were not intended by the parties taking an action.

Prompts. There was a strategy that arose in the military protocols, but not in the scientist's protocols, which depended on the interaction between experts. We have labeled these "prompts," because one of the experts would bring up an issue for the group to consider. Any tool we design to support expert analysis would naturally have a set of prompts that it might use to provoke the experts to consider different alternatives. We give examples of the prompts that occurred in the military protocols.

- **Downsides.** In considering different courses of action, such as whether to send US ships to the Malacca Straits, one of the experts often raised the question of what the downsides (or costs) would be.
- **Possible Actions.** One of the experts raised the possibility of multilateral action, after they had been considering unilateral action.
- **Legality.** One of the experts often raised the question of whether a particular action was legal under international law, such as Indonesia collecting fees for passage through the Straits of Malacca.

- **Countries Affected.** One of the prompts raised was what countries would be affected by any particular action.
- **Deception.** A particular issue that was raised on several occasions was whether an action was what it appeared to be, or whether it was a deception of some kind, such as the movement of troops by Iraq and Syria in the water rights scenario.

Conclusion. In the protocols collected from military experts, there were three different levels of analysis and two different types of analysis that the experts used. The three levels of analysis were concerned with different actors: (1) individuals and groups (e.g., the foreign minister of Turkey or the pirates), (2) countries (e.g., Syria or Indonesia), and (3) alliances (e.g., UN, NATO, or ASEAN). The two types of analysis involved (1) interpretation of actor's goals, intentions, and possible future actions, and (2) considering different courses of action with respect to the actors. This same distinction between interpretation and action arose in the wages problem given to scientists, where they were asked to analyze the reason for the decline in wages and to propose remedies for it.

The military protocols suggest a number of things for the design of a tool to support expert analysis. Clearly the kinds of prompts that occurred would be very useful, and each epistemic form suggests a number of prompts that could be posed to experts. It was also apparent that there were a number of different types of costs and benefits that the experts considered (e.g., financial, international relations) and these could act as prompts in doing a cost-benefit analysis in considering different courses of action. The protocols also provide a rich source of domain frameworks and key constructs that can be built into such a tool.

Design of a Tool to Support Expert Analysis

Based on our experiments we have begun to design a tool that would support analysts as they work on problems like those we used in the experiments. We see the tool as functioning interactively with analysts as they try to interpret a situation, and develop courses of action to deal with the situation. We will outline our preliminary design in terms of how the tool would support analysts faced with the military scenarios that we used in the experiments.

The tool we envision would prompt analysts to consider all the important actors in a situation, the stages of the developing action, the possible interpretations of actions by others, the possible courses of action, and the costs and benefits of different courses of action. Analysts may respond or not respond to any of the prompts. Each prompt they respond to may lead to further prompts in order to fill out the corresponding epistemic form.

The prompts support the construction of models of the situation. We see these models as comprising two aspects of the situation: 1) an interpretive analysis, where the goal is to determine the intentions of the different actors, and 2) an action analysis, where the goal is to consider different courses of action and their corresponding costs and benefits. The tool will support analysts to update their models as the situation or their understanding unfolds.

Interpretive Analysis

In order to prompt analysts to consider all the important actors in a situation we would prompt them to respond at the three levels identified in the protocols: 1) the individual and group level (Assad in Syria or the pirates in the Malaccan Straits), 2) the country level (Turkey or Indonesia), and 3) the institutional level (NATO or the UN). To identify the relevant countries and institutions, the system would prompt the analysts to consider all the countries and institutions in the region, where the situation is developing. For example, while the analysts in the pirate scenario considered Indonesia, Singapore, Malaysia, and China, they did not consider Thailand or Myanmar (Burma). This uses a spatial decomposition strategy to guide the analysis.

To guide the interpretation of the situation the system would prompt the analysts about the stage of development of the situation and the relations between the participants. In the water-rights scenario the expert analysts based their interpretation on a three-stage model: 1) negotiation between the conflicting parties, 2) military preparations, and 3) military conflict. When they saw troop movements before the negotiations had run their course, they interpreted them as designed to show seriousness, rather than as plans to take military action. This three-stage model in generalized form can provide a basis for prompting analysts in many situations. For example, in conflict situations the system can prompt the analysts to specify the stage of the conflict, their certainty with regard to that choice, and how they would interpret each action in light of that stage.

In the piracy scenario the experts did not consider negotiations with the pirates, probably because they are like terrorists who are not amenable to negotiation. So they jumped to considering courses of action in preparation for military action. The system would have prompted them to consider whether negotiations with the pirates were possible.

Another kind of interpretive prompt would support analysts in constructing causal chains such as that shown above in Figure 2 depicting one expert's analysis of what could happen in the water-rights scenario. The system would prompt the analysts to specify different actions participants might take at any point and the likelihood of that choice. It would then ask what actions other parties are likely to take in response. The system would ask the experts to decide for multiple actions, whether their projections are ORed together (where likelihoods should add to 1) or are ANDed together (where likelihoods are independent). This would enable the analysts to project possible scenarios out to as much depth as they feel is useful. The system can also prompt the analysts to project backwards to the precursors for actions taken, if that is helpful to them. Based on the expert's inputs, the system would automatically construct a diagram for causal analyses, such as shown in Figure 2.

In the protocols, the analysts raised the question a number of times as to whether the actions taken were what they appeared to be, or whether there was some deception going on. So for example, one of the analysts in the piracy scenario raised the question of whether the Chinese might be supporting the pirates to provide a diversion from the Chinese attempt to seize the Spratley Islands. We propose that the system prompt analysts to consider whether there is another possible interpretation involving deception for any important event that occurs.

Action Analysis

In order to support the analysts in deciding upon courses of action, we plan to encourage them to set up tables of the possible actions and their costs and benefits. An example of the kind of table we envision is shown below in Figure 3.

Likelihood of Success	Benefits	Costs
Alternative 1	Financial	Financial
	Military	Military
L=.8	International relations	International relations
	Popular support	Popular support
	Economic	Economic
Alternative 2	Financial	Financial
	Military	Military
L=.5	International relations	International relations
	Popular support	Popular support
	Economic	Economic

Figure 3. Example of a Cost-Benefit Epistemic Form

In order to fill out such a table the analysts would be prompted to consider different possible courses of action. The possible courses of action for the negotiating phase that were brought up in the protocols included:

- Have disputants meet together and discuss their differences.
- Provide mediation to come up with neutral, face saving solutions.
- Provide guarantees or resources to alleviate the concerns of the disputants.
- Provide pressure if they fail to agree, such as freezing assets, imposing sanctions, or military pressure.

The courses of action that were considered in the military-preparation phase included:

- Multilateral action, either by an institution (e.g. NATO) or by an ad-hoc coalition.
- Unilateral action.
- Pressure on other countries to take action (e.g. on Indonesia to stop the pirates).

Neither of the scenarios involved the actual planning of military actions, so that the respondents did not develop courses of action for the military-action phase, but the system could support them in making such decisions as well.

The likelihood of success came up in the expert's discussion of different alternatives, so that it makes sense for the system to prompt analysts to specify their best estimates of those likelihoods. In some cases they may feel that the likelihood of partial success is greater than the likelihood of overall success, so the system should allow them to specify likelihoods in more complex ways, if warranted.

In Figure 3 above we have shown several of the different kinds of costs and benefits the experts discussed in their protocols, which the system would use as prompts. One of the analysts kept asking the group to consider the "downsides" or costs of any action, because he knew that there is a natural human tendency to consider only the benefits, and he had trained himself to address the costs as well as benefits. Any type of potential benefit is also a type of potential cost, so we have listed the same set for both in Figure 3. We briefly describe the different types of costs and benefits in the Figure:

- **Financial benefits** refer to the money saved or the resources acquired, if an action is successful. **Financial costs** refer to such things as providing resources or paying others to do so.
- **Military benefits** refer to the experience gained from participating in an action and the evaluation of new weapon systems in combat. **Military costs** refer to the loss of personnel and resources.
- **International-relations benefits** refer to good relations that are developed with countries as they address a problem together. **International-relations costs** refer to the antagonism from other countries spawned by an action. **Legality** was central to several of the discussions, and it could be treated as part of international relations or as a separate category.
- **Popular-support benefits** refer to positive reactions from the population of a country to an action taken by that country. **Popular-support costs** refer to the corresponding negative reactions.
- **Economic benefits** refer to positive effects on the economy of a country resulting from an action. **Economic costs** refer to negative effects on the economy.

There are other possible types of costs and benefits that may arise in other scenarios, so that we would have to study experts working with other problems to determine the best set of prompts to use.

Conclusion

Our studies of expert analyses have revealed many important aspects of the process by which experts create models of a situation, beyond our preliminary typology of epistemic forms and games. While epistemic forms and games did turn out to be critical aspects of the analysis process, we have identified a number of other critical components, i.e. key constructs, domain frameworks, heuristics, and prompts that also serve to guide the process. We were also impressed by how similarly the scientists and military experts approached problems in their very different domains of expertise, which allowed us to construct a uniform framework for the analysis process.

We think the application of this work with the highest potential impact would be to develop a computer tool that facilitated expert analysis, based on the theory of epistemic forms and games. As we have argued elsewhere (Collins & Ferguson, 1993) computer tools like STELLA and Model It (Jackson, Stratford, Krajcik, & Soloway, 1994) support analysts to construct models, using a single epistemic form. Our data support the fact that experts use a variety of epistemic forms in constructing their understanding of a situation, and that the models they construct are based on multiple epistemic forms embedded within each other. Therefore we think that the next generation of tools to support model building will need to provide multiple forms that analysts can use to construct their interpretations.

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